NRC Publications Archive
Archives des publications du CNRC

# Investigation of the mechanical properties of St. Lawrence River ice

Gold, L. W.; Krausz, A. S.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.
For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

**Publisher's version / Version de l'éditeur:**
https://doi.org/10.1139/t71-017
*Canadian Geotechnical Journal, 8, 2, pp. 163-169, 1971-05*

**NRC Publications Archive Record / Notice des Archives des publications du CNRC :**
https://nrc-publications.canada.ca/eng/view/object/?id=33c53c54-3fe7-481c-b468-482d008e7377
https://publications-cnrc.canada.ca/fra/voir/objet/?id=33c53c54-3fe7-481c-b468-482d008e7377

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada Conseil national de recherches Canada

Ser
TH1
N21r2
no. 470
c. 2

BLDG

1710

ANALYZED

NATIONAL RESEARCH COUNCIL OF CANADA
CONSEIL NATIONAL DE RECHERCHES DU CANADA

# INVESTIGATION OF THE MECHANICAL PROPERTIES OF ST. LAWRENCE RIVER ICE

BY

L. W. GOLD AND A. S. KRAUSZ

*Reprinted from*
CANADIAN GEOTECHNICAL JOURNAL
VOL. 8, NO. 2, MAY 1971
p. 163

BUILDING RESEARCH
- LIBRARY -
JUN 29 1971
NATIONAL RESEARCH COUNCIL

RESEARCH PAPER NO. 470
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA
May 1971

Price 25 cents

NRCC 11820

This publication is being distributed by the Division of Building Research of the National Research Council of Canada. It should not be reproduced in whole or in part without permission of the original publisher. The Division would be glad to be of assistance in obtaining such permission.

Publications of the Division may be obtained by mailing the appropriate remittance (a Bank, Express, or Post Office Money Order, or a cheque made payable at par in Ottawa, to the Receiver General of Canada, credit NRC) to the National Research Council of Canada, Ottawa. Stamps are not acceptable.

A list of all publications of the Division is available and may be obtained from the Publications Section, Division of Building Research, National Research Council of Canada, Ottawa 7, Canada.

CISTI / ICIST
3 1809 00211 2818

ANALYZED

# Investigation of the Mechanical Properties of St. Lawrence River Ice[1]

L. W. GOLD[2] AND A. S. KRAUSZ[3]
*Division of Building Research, National Research Council of Canada, Ottawa, Canada*

Received September 28, 1970

Observations are reported on the stress–strain behavior at $-9.5 \pm 0.5$ °C of four types of ice obtained from the St. Lawrence River. The ice was subject to nominal rates of strain covering the range $2.1 \times 10^{-5}$ min$^{-1}$ to $5.8 \times 10^{-2}$ min$^{-1}$. A ductile-to-brittle transition was observed for strain rate of about $10^{-2}$ min$^{-1}$. In the ductile range the four types had an upper yield stress that increased with strain rate according to a power law.

Le mémoire rapporte des observations sur le comportement contrainte–déformation à $-9.5 \pm 0.5$ °C pour quatre types de glace provenant du fleuve Saint-Laurent. La glace a été soumise à des vitesses nominales de déformation variant entre $2.1 \times 10^{-5}$ min$^{-1}$ à $5.8 \times 10^{-2}$ min$^{-1}$. Une transition de l'état ductile à l'état fragile a été observée à des vitesses de déformation d'environ $10^{-2}$ min$^{-1}$. Pour les quatre types de glace, la contrainte de rupture a augmenté avec un accroissement de la vitesse de déformation selon une loi de puissance.

The development of design criteria for structures that must withstand ice pressures and the improvement of icebreaker operations is of great economic significance. A series of tests was carried out by the National Research Council of Canada on the mechanical properties of ice formed in the winter of 1968–1969 in order to provide information for the evaluation of the performance of icebreakers operating on the St. Lawrence River. The ice was obtained from sites at Repentigny on the St. Lawrence River between Lanoraie and Cap St. Michel, on Lac St. Pierre and in the harbour of Montreal. This paper reports the results of the tests.

## Experimental Procedure

*Identification of the Specimens*

Ice covers are not usually composed of only one type of ice. The type that forms depends on the conditions at the time of formation and can change either abruptly or gradually. As strength depends on the ice type, it was necessary to identify the ice before preparing specimens for testing.

Thin sections were cut parallel and perpendicular to the original surface of the ice cover, those cut perpendicular to the surface extending through the full thickness of the cover. Each section was 4 in. (10 cm) wide. They were viewed with polarized light to determine the location of the layers in the cover, the type of ice associated with each layer, and the grain size. The ice was classified (Table 1) according to the classification developed by the Ice Laboratory at Laval University (Michel and Ramseier 1969). Measurements were also made of the density of each well-defined layer.

*Specimen Preparation*

Rectangular specimens 2 × 4 × 10 in. (5 × 10 × 25 cm) and 1.5 × 3 × 7.5 in. (4 × 8 × 19 cm) were prepared by milling. The smaller size specimens

TABLE 1. Genetic classification of ice (Michel and Ramseier 1969)

Secondary ice (develops from primary)
S1: Columnar-grained; C axis vertical; crystal size increases with depth, and is usually large to extra large; grain shape irregular.
S2: Columnar-grained; C axes tend to become perpendicular to long direction of columns with growth; crystal size small to large, increasing more rapidly with depth than type S1.
S4: Congealed frazil slush: grain boundaries are irregular, their shape is equiaxed to tabular, and crystallographic orientation is random.

Tertiary ice
T1: Snow ice; crystallographic orientation is random; grains are equiaxed; the grain size small to medium.
R1: Agglomerate ice; grain size can be from fine to extra large, and the shape can vary from equiaxed to tabular to columnar, with the crystal boundaries regular to angular in shape. Crystallographic orientation can be from random to preferred.

Grain size
Small: Grain diameter less than 1 mm.
Medium: Grain diameter between 1 and 5 mm.
Large: Grain diameter between 5 and 20 mm.
Very large: Grain diameter greater than 20 mm.

[1]NRCC 11820.

[2]Geotechnical Section, Division of Building Research, National Research Council of Canada.

[3]Formerly Geotechnical Section, Division of Building Research, National Research Council of Canada; presently Department of Mechanical Engineering, University of Ottawa.



3400187

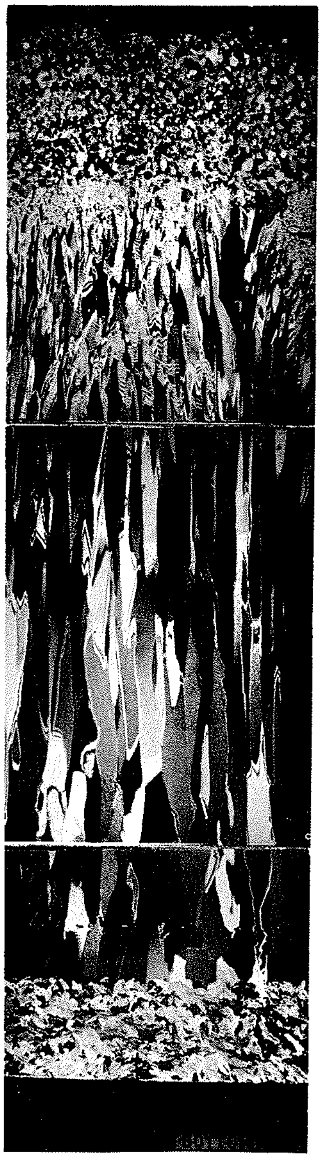
| Location of Sample: Longueuil Montreal Harbour | Ice type and grain size | Average density g/cc | Location of specimens |
|---|---|---|---|
|  | | | |
| | T1 med. | 0.897 | 3-1 |
| | R1 med. | 0.906 | 3-3<br>3-4 |
| | S2 large | 0.916<br>0.910<br>0.916 | 3-5<br>3-6<br>3-7<br>3-8 |
| | S4 med. to large | 0.898<br>0.911 | 3-9<br>3-10 |

FIG. 1. Thin section of ice from the St. Lawrence River.

had to be used at the higher rates of strain to keep the loads within the capacity of the testing machine.

Each specimen was cut so that the face 4 × 10 in. (10 × 25 cm) or 3 × 7.5 in. (8 × 19 cm) was parallel to the original ice surface. The columnar grained ice specimens were always cut so that the long direction of the grains was perpendicular to the applied load.

*Testing Method*

All tests were carried out in compression at an approximately constant rate of strain, applied by a Wykeham Farrance 10 000-lb (4500-kg) capacity soil-testing machine. This machine provided a maximum rate of crosshead movement of 0.3 in./min (0.8 cm/min). The lowest rate used was 2.5 × $10^{-4}$ in./min (6.4 cm/min). These rates corresponded to nominal strain rates of 5.8 × $10^{-2}$ $min^{-1}$ to 2.1 × $10^{-5}$ $min^{-1}$. All tests were conducted at −9.5 ± 0.5 °C.

The strain was determined by measuring the relative displacements between the upper and lower loading plates, using four linear differential transformers mounted on each side and on the face of the specimen. The load was measured with a load cell that had been calibrated previously with a 10 000-lb capacity Tinius Olsen proving ring. A linear differential transformer was used to determine the deflection of the load cell. Both the load and the strain were recorded with a Hewlett–Packard 2010H data-logging system and monitored with a two-pen 7100 B strip chart recorder.

## Experimental Results

*Specimen Classification and Density*

A typical thin section of ice from the Montreal harbour site is presented in Fig. 1. The layers are identified and the associated ice type and density presented in the columns on the right-hand side. This photograph shows the great variation that can occur in the ice cover of a river such as the St. Lawrence. The ice cover in Montreal harbour appears to have begun with the accumulation of frazil or snow slush. The initial buildup was of agglomerate type R1 ice, which subsequently developed into columnar-grained type S2. A layer of frozen frazil, type S4, formed at the bottom, and snow ice, type T1, developed at the upper surface. Histories of similar complexity occurred at Repentigny and the two Lac St. Pierre sites.

Specimens for testing were cut from the layers of types S1, S2, S4, T1, and R1 ice. Only two tests were carried out on type R1 because of its scarcity. Typical stress–strain curves for types S1, S2, S4, and T1 ice are shown in Figs. 2, 3, and 4 for nominal strain

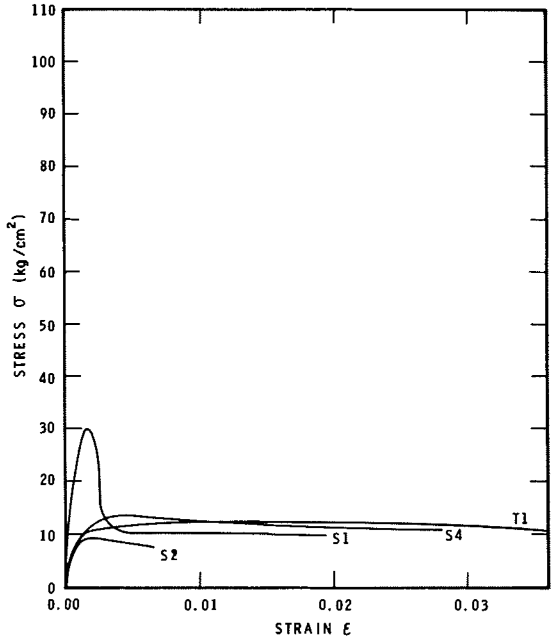



FIG. 2. Strain dependence of the stress for ice from St. Lawrence River. Strain rate, 2 × $10^{-5}$ $min^{-1}$; temperature, −9.5 °C.

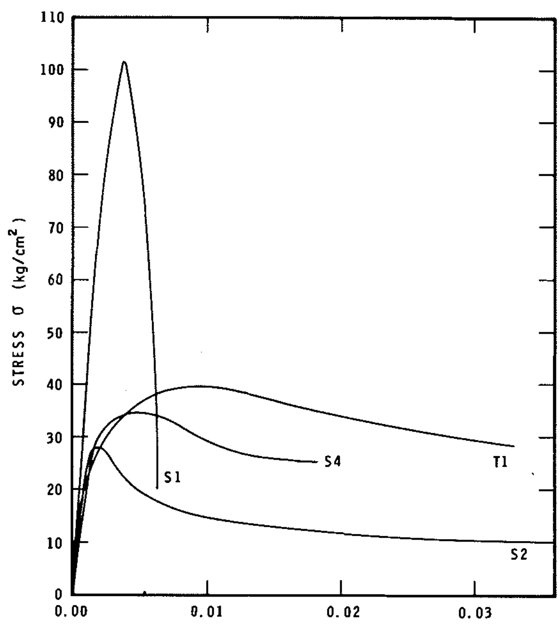



FIG. 3. Strain dependence of the stress for ice from St. Lawrence River. Strain rate, 1 × $10^{-3}$ $min^{-1}$; temperature, −9.5 °C.

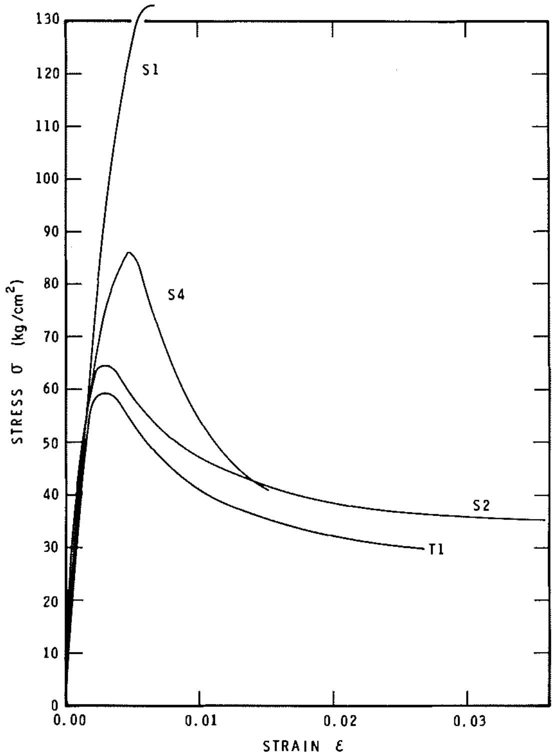



FIG. 4. Strain dependence of the stress for ice from St. Lawrence River. Strain rate, $1 \times 10^{-2}$ min$^{-1}$; temperature, −9.5 °C.

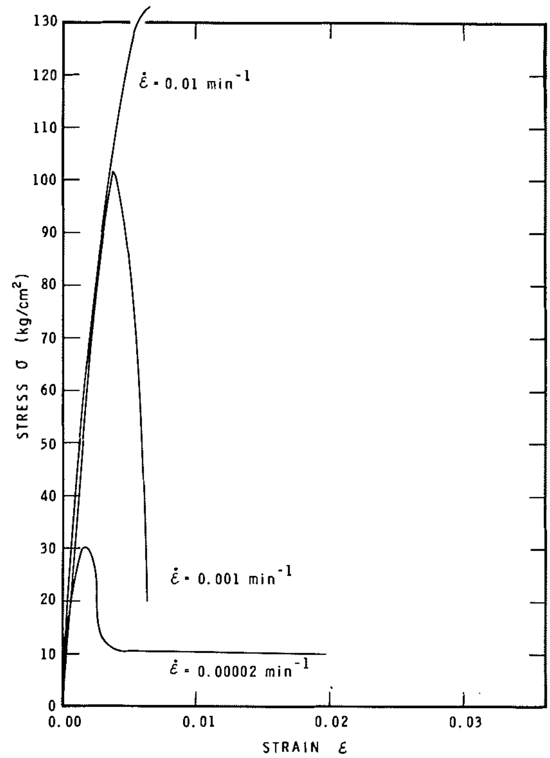



FIG. 5. Dependence of stress on strain and strain rate for type S1 ice. Temperature, −9.5 °C.

rates of $2 \times 10^{-5}$, $1 \times 10^{-3}$, and $1 \times 10^{-2}$ min$^{-1}$, respectively. The strain rate dependence of the stress–strain behavior of the four types is shown in Figs. 5, 6, 7, and 8. The behavior of type R1 ice was similar to that of type T1 ice under the same test conditions.

It may be seen that a maximum occurs in the stress (upper yield stress, $\sigma_{uy}$) for the examples that have been presented. The upper yield stress increases with increase in rate of strain. A ductile-to-brittle transition in behavior was observed at strain rates of about $10^{-2}$ min$^{-1}$. For strain rates just below the transition, specimens fractured after yield at strains of less than $10^{-2}$ min$^{-1}$ (see Fig. 4, curve S1). For strain rates above the transition the specimens fractured before the upper yield stress was attained.

The strain rate dependence of the upper yield stress is of great importance in calculations of the forces that ice covers can exert. In the present study it was observed that the strain rate dependence of the upper yield stress could be expressed by

$$[1] \qquad \sigma_{uy} = \sigma_o\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)^n = 203\dot{\varepsilon}^{0.25}\ \text{kg/cm}^2$$

as shown in Fig. 9.

Crack formation was a characteristic feature of the deformation. The first cracks were usually observed at a load of about 0.5 $\sigma_{uy}$. Cracking activity was usually uniform prior to the upper yield and increased in severity after this point was passed. At strain rates greater than about $5 \times 10^{-5}$ min$^{-1}$ the cracking activity was sufficiently severe to cause the resistance of the specimen to deformation to decrease continuously.

Deformation up to the yield point and beyond was sufficiently uniform for the stress distribution at yield to be considered uniform within the usual limitations of a compression test. In the later stage of low strain rate tests

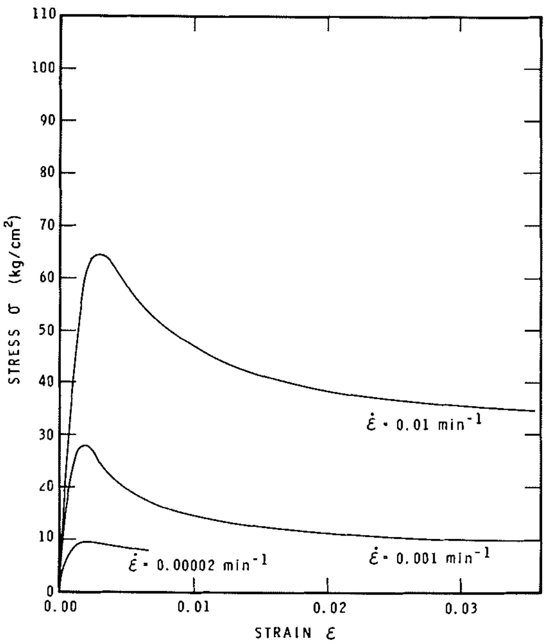



FIG. 6. Dependence of stress on strain and strain rate for type S2 ice. Temperature, −9.5 °C.

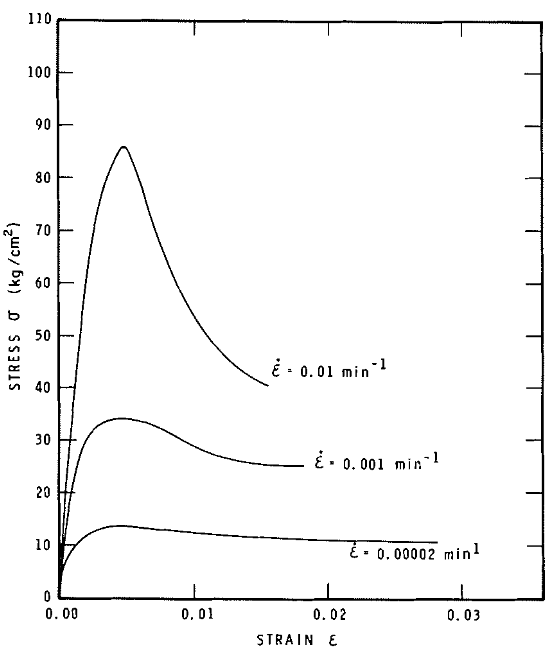



FIG. 7. Dependence of stress on strain and strain rate for type S4 ice. Temperature, −9.5 °C.

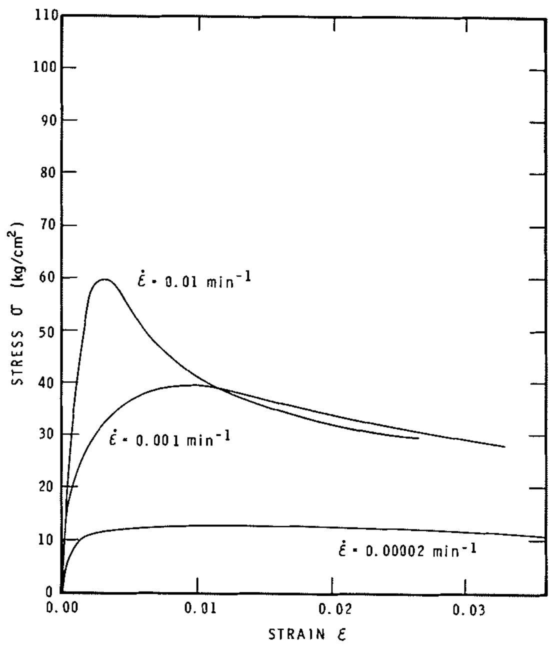



FIG. 8. Dependence of stress on strain and strain rate for type T1 ice. Temperature, −9.5 °C.

extensive barrelling sometimes occurred, followed by buckling. Despite the very severe cracking that was associated with this condition the specimens did not break apart.

## Discussion

The observations shown in Fig. 9 indicate that the difference in the yield or failure stress of natural granular type T1 ice, frazil type S4, and columnar-grained type S2 is less than the scatter in the results for one type of ice subject to the given conditions of loading. This result is significant for engineering calculations. As may be seen in Fig. 1, two or three of these ice types can occur simultaneously in a cover. The determination of the strength of such a layered structure would be extremely difficult if the strengths of the various types of ice differed significantly from each other. If it can be assumed that an ice cover composed of layers of these types of ice is homogeneous, it would greatly simplify calculations. It is important to note that type S1 ice, oriented so that the load was applied perpendicular to the long direction of the columns, was significantly stronger than the other three types.

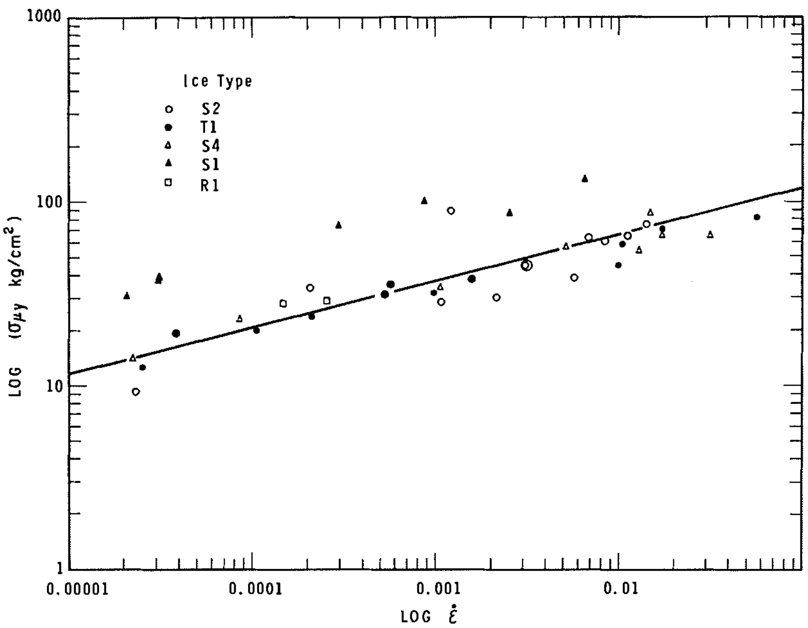



FIG. 9. Strain rate dependence of the yield and failure strength of types S1, S2, S4, R1, and T1 ice, $\sigma$ in kilograms per centimeter$^2$, $\epsilon$ in minute$^{-1}$.

It was observed that the ductile-to-brittle transition occurred for columnar-grained types S1 and S2 ice at strain rates of about $10^{-2}$ min$^{-1}$. This also appeared to be about the strain rate for the initiation of the transition for type S4 ice. The rate of crosshead movement of the testing machine was not great enough, unfortunately, to establish the transition rate for the granular, type T1 ice. Neither was it possible to extend the observations sufficiently beyond the ductile-to-brittle transition point to establish the general trend in the dependence of the ultimate strength on strain rate. Limited information presented by Jellinek (1956) for tensile tests on freshwater ice, by Peyton (1968) for sea ice, and by Russian investigators indicates that a maximum occurs near the transition point, and that the ultimate strength then gradually decreases with increasing rate of strain.

## Conclusions

Study of natural, granular, type T1 ice, columnar types S1 and S2, and frazil type S4 showed that for strain rates less than about $10^{-2}$ min$^{-1}$ these ice types exhibited a yield behavior under constant strain rate conditions. A ductile-to-brittle transition occurred at a strain rate of about $10^{-2}$ min$^{-1}$. In the ductile region the logarithm of the upper yield stress was linearly dependent on the logarithm of the strain rate. There appeared to be no significant difference, from an engineering point of view, in the strain rate dependence of the upper yield stress for types T1, S2, and S4 ice. The ductile-to-brittle transition of granular type T1 ice occurred at a higher rate of strain than for columnar-grained ice. Large grained, type S1 ice loaded so that the stress was perpendicular to the long direction of the columns had a significantly higher yield stress than granular, frazil, and type S2 ice subjected to the same rate of strain.

## Acknowledgments

The authors are grateful to the St. Lawrence Ship Channel Division of the Federal Department of Transport for providing the ice used in this study. They also wish to acknowledge with thanks the assistance of G. Mould and W. Ubbink in carrying out the observations.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

JELLINEK, H. H. G. 1965. The influence of imperfections on the strength of ice. Proc. Phys. Soc. **21**, pp. 797–814.

MICHEL, B., and RAMSEIER, R. O. 1969. Classification of river and lake ice. Presented to the 6th Snow and Ice Conference, Snow and Ice Subcommittee, Associate Committee on Geotechnical Research, National Research Council of Canada, 1969.

PEYTON, H. R. 1968. Sea ice forces. *In* Ice pressures against structures. Associate Committee on Geotechnical Research, National Research Council of Canada. Technical Memorandum No. 92, pp. 117–123.